

CHANGE ISSUE – RTCA/DO-242

MASPS for ADS-B

Rev. A

Tracking Information (committee secretary only)	
Change Issue Number	2
Submission Date	12/27/00
Status (open/closed/deferred)	Rev. A - CLOSED
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Short Title for Change Issue:	Altitude rate is problematic and should be deleted as a required ADS-B message element.
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MASPS Document Reference:		Originator Information:	
Entire document (y/n)		Name	Stephen Heppe / ADSI Inc
Section number(s)		Phone	+1 703-589-1522
Paragraph number(s)	2.1.2.2.2.2	E-mail	steveheppe@adsi-m4.com
Table/Figure number(s)	Table 2-2	Other	

Proposed Rationale for Consideration (originator should check all that apply):	
X	Item needed to support of near-term MASPS/MOPS development
X	DO-260/ED-102 1090 MHz Link MOPS Rev A
X	ASA MASPS
	TIS-B MASPS
X	UAT MOPS
	Item needed to support applications that have well defined concept of operation
	Has complete application description
	Has initial validation via operational test/evaluation
	Has supporting analysis, if candidate stressing application
	Item needed for harmonization with international requirements
	Item identified during recent ADS-B development activities and operational evaluations
	MASPS clarifications and correction item
X	Validation/modification of questioned MASPS requirement item
	Military use provision item
	New requirement item (must be associated with traffic surveillance to support ASAS)

Nature of Issue:	<input type="checkbox"/>	Editorial	<input type="checkbox"/>	Clarity	<input type="checkbox"/>	Performance	X	Functional
<u>Issue Description:</u> <p>Altitude rate is described as climbing or descending with rates reported up to 32,000 fpm. The MASPS variously requires barometric or inertially augmented barometric, or geometric, altitude rate depending on NUC category. Table 2-2 indicates that it is a required message element for all applications listed. The rationale for altitude rate was originally based on simulations which attempted to demonstrate improved warning time for “incursions” during vertical maneuvers (see DO-242 Appendix J section J.3.1.1.2). The simulations seem to indicate that reporting altitude rate can marginally improve warning time when an aircraft is climbing through, or leveling-off at, own ship’s altitude (note: detailed simulation results are not contained in DO-242). However, the operations concept to generate this information on the transmit side, and use it on the receiving side, has never been described. Furthermore the existing simulations do not account for updrafts and downdrafts which can significantly affect instantaneous vertical rate (especially in extreme weather conditions). Variations in vertical rate on the order of ± 1000 fpm occur with relatively high probability. Since the vertical rate experienced by an aircraft is subject to large-amplitude short-term fluctuations, some form of averaging or smoothing will likely be required in order to avoid false alarms. Any form of averaging would require standardization and extensive analysis to ensure it was appropriate for all aircraft types. But if the averaging time stretches to even a few seconds, it would be more appropriate (and consume fewer bits) to simply take the difference between the altitudes reported in the last two messages.</p>								

Originator's proposed resolution:

Delete altitude rate as a required message element for any application. This will make room for other sorts of data with more operational significance. Receiving stations can determine an average vertical rate by taking the difference of the altitudes reported in the last two messages. This is straightforward and does not consume any additional bits. The bits saved by this deletion can then be used for other sorts of data which have a well-developed operations concept.

Working Group 6 Deliberations:

May 24, 2001: This Issue Paper was discussed by the ad hoc group at their May 2001 meeting. Jonathan Hammer presented 242A-WP-5-10 in response to Action Items 2-26 and 3-8. The conclusion of Jonathan's analysis is that Altitude Rate does need to be a required ADS-B message element, and therefore, this IP should be rejected. The ad hoc group agreed to consider an alternate proposed resolution which would require only the "best source" for altitude rate to be broadcast. This proposal was documented and presented as 242A-WP-5-09a, and is included with this Issue Paper as Attachment A. This Issue Paper will be addressed DO-242A, and an Action Item (AI 5-11) was given to the original author of this IP (Steve Heppe) to coordinate a teleconference before the July ad hoc meeting to discuss the merits of the proposed resolutions.

July 19, 2001: At the July WG6 meeting, it was agreed that the "best source" of altitude rate should be used and transmitted by ADS-B. It was further agreed that altitude rate will remain a required SV element. Action Items 6-13 and 6-19 were given to Jonathan Hammer to produce changed text for 2.1.2.2.2.2 "Altitude Rate" and a new appendix characterizing a simple Kalman filter for smoothing Barometric Altitude.

August 30, 2001: At the August WG6 meeting, Jonathan Hammer presented working paper 242A-WP-7-11 in response to action item 6-19 and paper 242A-WP-7-12 in response to action items 6-13. 242A-WP-7-11 proposes altered text for 2.1.2.2.2.2 "Altitude Rate" and 242A-WP-7-12 is a new appendix characterizing a simple Kalman filter to smooth Barometric altitude. Both of these papers were approved by WG6 and are found as attachments B and C of this Issue Paper. The text from these papers will be incorporated into DO-242A and will close this Issue Paper. As a final conclusion for this issue paper, Jonathan will propose an addition to Appendix J on his study showing the hierarchy of the quality of altitude rate sources.

September 27, 2001: Jonathan Hammer reported that Bob Grapple from MIT Lincoln Laboratory contacted him to report that there are other filters that would perform better than the Kalman filter documented in Jonathan's proposed appendix (Attachment C of this Issue Paper). Jonathan stated he didn't mind which filtering algorithm is referenced, as long as a standard is set. It was proposed to reference the filter used by TCAS in DO-185A instead of having an additional appendix. This decision affects the already agreed to resolution of IP02. [AI 8-4] Jonathan will rewrite this section to reflect the agreements reached by WG6 and referencing DO-185A rather than the new appendix.

October 26, 2001: It was realized at the October WG6 meeting that any smoothing algorithm was not useful unless the quality of the data input was known by the receiving system. This led to a lengthy discussion on how to best handle this in Revision A. This discussion concluded with the following agreements:

- In section 2.1.2.11.5.1, instead of the RSVM Quality flag, there will be a two-bit table for barometric altitude accuracy, barometric altitude rate accuracy and barometric altitude rate lag.
- A statement will be added that if the ADS-B derived baro altitude rate does not meet the requirements of the baro altitude quality table, baro altitude rate will not be transmitted.
- The barometric altitude accuracy code reflects the quality both of externally provided barometric altitude and externally or internally provided barometric altitude rate.
- An Issue Paper will be written regarding the analysis needed to address the accuracy and latency requirements for altitude rate in a future MASPS revision. [AI 9-8]

(continued)

Working Group 6 Deliberations (continued):

February 22, 2002: During final review of the draft DO-242A by WG6 at their February meeting, this Issue paper was revisited. It had previously been agreed by WG6 that Altitude Rate must still be a required element in the State Vector Report, but that it should be permissible to only transmit altitude rate from one source when both are available. The MASPS language provided in 242A-WP-12-01 was accepted and this text will close this Issue Paper.

Working Group 6 Final Resolution:

Below are sections 2.1.2.8 and 3.4.3.16 from the draft DO-242A sent to RTCA on March 4, 2002. The text addressing this IP are shown in blue.

2.1.2.8 Vertical Rate

Transmitting A/Vs that are not fixed or movable obstacles and that are not known to be on the airport surface **shall** (R2.23) provide vertical rate.

Note 1: In this context, a “movable obstacle” means an obstacle that can change its position, but only slowly, so that its horizontal velocity may be ignored.

Vertical Rate **shall** (R2.24) be designated as climbing or descending and **shall** (R2.25) be reported up to 32,000 feet per minute (fpm). Barometric altitude rate is defined as the current rate of change of barometric altitude. Likewise, geometric altitude rate is the rate of change of geometric altitude. At least one of the two types of vertical rate (barometric and geometric) **shall** (R2.26) be reported.

If only one of these two types of vertical rate is reported, it **shall** (R2.27) be obtained from the best available source of vertical rate information. If differentially corrected GPS (WAAS, LAAS, or other) is available, geometric altitude rate as derived from the GPS source should be transmitted. If differentially corrected GPS is not available, but inertial augmented barometric altitude rate is available, inertial augmented barometric altitude rate will be the preferred source of altitude rate information.

Note 2: Future versions of this MASPS are expected to include requirements on the accuracy and latency of barometric altitude rate.

Note 3: Vertical rate is reported in the SV report (§3.4.3) below.

3.4.3.16 Vertical Rate Field

The “vertical rate” field in the SV report contains the altitude rate (§2.1.2.8) of an airborne ADS-B participant. This **shall** (R3.86) be either the rate of change of pressure altitude or of geometric altitude, as specified by the “vertical rate type” element in the MS report. The range of reported vertical rate **shall** (R3.87) accommodate up to ± 32000 ft/min for airborne participants. Geometric vertical rate **shall** (R3.88) be communicated and reported with a resolution sufficiently fine that it does not compromise the accuracy reported in the NAC_V field of the Mode-Status report. Moreover, vertical rate **shall** (R3.89) be communicated and reported with a resolution sufficiently fine that it does not compromise the one-sigma maximum ADS-B contribution to vertical rate error, σ_{vv} , listed in Table 3-4(a): that is, 1.0 ft/s for airborne participants.

Note: Future versions of this MASPS will require that the resolution of barometric altitude rate be sufficiently fine that it does not compromise the Barometric Altitude Quality (BAQ) field (§3.4.4.14) reported in the MS report, which is not defined in this version of the MASPS.

Addendum to Issue Paper Number 2

Tony Warren, May 21, 2001

Recent simulations conducted by Jonathan Hammer were performed to examine the effect of including high quality altitude rate data (augmented GPS geometric altitude and altitude rate), low quality altitude rate data (baro altitude and altitude rate), and derived altitude and altitude rate data given 3 second updated altitude only data on a vertical conflict alerting problem. The simulation results showed that detection alert times were much better with altitude rate data than without, and that use of high-quality geometric altitude and altitude rate data was significantly better than use of lower quality baro altitude and altitude rate data.

Discussion of these results within the Ad Hoc MASPS working group led to the conclusion that there is value to retaining altitude rate data in the revised ADS-B MASPS. However, two questions were brought up in the discussion which warrant further study:

(1) Is it necessary for all aircraft including basic VFR aircraft to transmit altitude rate data if the quality of such data is poor, and such aircraft are unlikely to participate in the kind of conflict alerting scenarios envisioned in the reference simulations?

This question is not addressed in this addendum, but may be addressed in a new issue paper dealing with class codes, i.e. it may be necessary for ADS-B aircraft to transmit some means of specifying functional capability, in addition to NIC / NAC state vector integrity and accuracy codes, to differentiate those aircraft which need to support ADS-B applications using high quality altitude rate data.

(2) Is it necessary to broadcast both geometric and baro altitude rate if both (or multiple) sources are available, i.e. why not broadcast the best source of altitude rate data for the purpose of short term altitude prediction and conflict alerting?

The main issue with this idea is that it is not clear whether one can substitute geometric altitude rate for baro rate or visa versa. However, it can be shown that the two quantities can be directly related to one another by the following equation, valid for non-standard atmosphere conditions (Burrows, Ref [1]):

$$h_dot = (Tk / Tstd) * hp_dot$$

Where h_dot denotes geometric altitude rate
 hp_dot denotes pressure altitude rate
 Tk denotes actual temperature relative to absolute zero
 $Tstd$ denotes standard temperature at pressure altitude hp .

Now the addendum author submits that it is feasible to relate one version of altitude rate to the other with acceptable percent accuracy using the above equation, except in rare circumstances, and for limited altitude ranges, i.e. for temperature inversions near the earth boundary layer (typically extending no more than 3000 ft AGL). In most cases of

interest, the receiving aircraft can use delta-ISA (temperature difference from standard temperature) onboard the receiving aircraft as a means of approximating T_k for the transmitting source aircraft, i.e.

$$T_k \sim T_{std}(h_p) + \text{delta_ISA}$$

Thus it is possible in most cases of interest to directly relate geometric altitude rate to baro altitude rate given one transmitted altitude rate and an estimate of delta_ISA. Even when the above approximation is not valid, the error due to non-standard temperature profile rarely exceeds 10%, which is small compared to the short term variations in vertical rate on climb (which can be up to 1000 ft/min according to recent NASA Ames studies).

Consequently, given the above simulation results, we recommend consideration of the following alternative to deletion of altitude rate data:

Alternative Proposal: Change the ADS-B MASPS to require broadcast of the best source of altitude rate, and the type of altitude rate provided, e.g. geometric or baro based altitude rate. In the case of aircraft having only one source of data, they would broadcast that source when available. Otherwise, such aircraft would determine which data source was most accurate and appropriate for short term altitude predictions and broadcast that data source. This proposal would reduce the state vector from supporting two altitude rate quantities to one, conserving message bandwidth for other potential uses.

Reference:

[1] J.W. Burrows and A. Chakravarty, "Time Controlled Aircraft Guidance in Uncertain Winds and Temperatures," American Control Conference, pp.191-197, 1984.

Below is Jonathan's proposed paragraph 2.1.2.2.2 to close IP02, Altitude Rate Requirements. This proposal is in response to Action Item 6-19.

2.1.2.2.2 Altitude Rate

Altitude rate shall (R2.1) be designated as climbing or descending and shall be reported up to 32,000 feet per minute (fpm). Barometric altitude rate is defined as the current rate of change of barometric altitude. ~~The geometric altitude rate of the state vector is measured along the line from the origin of the WGS 84 reference system to the current position of the A/V.~~ Likewise, geometric altitude rate is defined as the current rate of change in geometric altitude. ~~For NUC_p values 8 and 9, geometric altitude rate shall (R2.24) be reported. For other NUC values, barometric altitude rate or inertially augmented barometric altitude rate shall (R2.25) be reported.~~ The best available source of altitude rate information should be used to derive an altitude rate for broadcast. If differentially corrected GPS (WAAS, LAAS, or other) is available, geometric altitude rate as derived from the GPS source should be transmitted. If differentially corrected GPS is not available, but inertial augmented barometric altitude rate is available, inertial augmented barometric altitude rate will be the preferred source of altitude rate information. In the absence of GPS or inertial augmented barometric rate, barometric altitude rate may be transmitted. A recommended Kalman filtering algorithm for deriving barometric altitude rate is provided in appendix ???. Alternative algorithms or direct measurement sources may be used to derive barometric altitude rate if it is demonstrated that the performance of the alternative is at least as good as that of the algorithm described in appendix ???.

MITRE

NOTE

To: RTCA SC-186 WG6

Date: 14 August 2001

From: J. B. Hammer

Subject: A Simple Kalman Filter for Smoothing Barometric Altitude

1.0 Kalman Filter

The Kalman filter suggested for smoothing barometric height consists of a simple, two state Kalman filter. The filter's state consists of position and velocity.

Linear dynamics are assumed. The filter takes as input the measured altitude, the previous track state, and the previous track state covariance. The filter also requires as input the time of the measurement. The filter produces as output an updated track state and covariance.

2.0 Filter State and Covariance

The filter maintains a state consisting of position and velocity and a state covariance matrix which represents the uncertainty in the state estimate.

The filter state estimate in the altitude dimension is represented by the vector $\begin{pmatrix} \hat{z} & \hat{\dot{z}} \end{pmatrix}$. The covariance matrix of the state estimate in the x-dimension is represented by the matrix:

$$\begin{pmatrix} \mathbf{S}_{\hat{z}}^2 & \mathbf{S}_{\hat{z}\hat{\dot{z}}}^2 \\ \mathbf{S}_{\hat{\dot{z}}\hat{z}}^2 & \mathbf{S}_{\hat{\dot{z}}}^2 \end{pmatrix}$$

where

$\mathbf{S}_{\hat{z}}^2$ represents the variance in the position estimate;

$\mathbf{S}_{\hat{\dot{z}}}^2$ represents the variance in the velocity estimate;

$\mathbf{S}_{\hat{z}\hat{\dot{z}}}^2$ represents the covariance of position and velocity.

3.0 Initial State and Covariance

Before any measurements are received, the state estimates and the state covariance matrix are initialized. The state estimate is initialized by setting both the position and velocity estimate to zero. The state covariance matrix is initialized according to equation 1:

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$$\begin{pmatrix} \mathbf{s}_{\hat{z}}^2 & \mathbf{s}_{\hat{z}\hat{z}}^2 \\ \mathbf{s}_{\hat{z}\hat{z}}^2 & \mathbf{s}_{\hat{z}}^2 \end{pmatrix} = \begin{pmatrix} \infty & 0 \\ 0 & \infty \end{pmatrix} \quad (1)$$

For the purposes of an actual implementation, infinity can be represented by a large real number.

4.0 Kalman Filter Steady State Algorithm

The standard Kalman filter consists of five steps:

1. State Extrapolation
2. Covariance matrix extrapolation
3. Residual Calculation
4. State vector update
5. Covariance matrix update.

The first two steps are identical regardless of whether the measurement is a position, velocity, or both. The last three steps depend on the form of the measurement.

4.1 State Extrapolation

The first step in the filter is to extrapolate the state estimates to the time of the current measurement. Equations 2 detail the mechanics of the state extrapolation:

$$\begin{aligned} \hat{\hat{z}} &= \hat{z} + \hat{\dot{z}}(dt) \\ \hat{\dot{z}} &= \hat{\dot{z}} \end{aligned} \quad (2)$$

where

$\hat{\hat{z}}$ is the predicted (extrapolated) barometric altitude;
 $\hat{\dot{z}}$ is the predicted barometric altitude rate;
 \hat{z} is the current barometric altitude estimate;
 $\hat{\dot{z}}$ is the current barometric altitude rate estimate;
 dt is the time difference between the current measurement and the last state update.

4.2 Covariance Matrix Extrapolation

The next step in the filtering process is the extrapolation of the covariance matrix.

$$\mathbf{s}_{\hat{\hat{z}}}^2 = \mathbf{s}_{\hat{z}}^2 + (dt)^2 \mathbf{s}_{\hat{\dot{z}}}^2 + 2dt \mathbf{s}_{\hat{z}\hat{\dot{z}}} + \frac{Q(dt)^4}{4} \quad (3)$$

$$\mathbf{s}_{\hat{\dot{z}}}^2 = \mathbf{s}_{\dot{\hat{z}}}^2 + (dt)^2 Q \quad (4)$$

$$\mathbf{s}_{\hat{\hat{z}}\hat{\dot{z}}} = \mathbf{s}_{\hat{\dot{z}}\hat{\hat{z}}} = \mathbf{s}_{\hat{z}\hat{\dot{z}}} + (dt) \mathbf{s}_{\hat{\dot{z}}}^2 + \frac{(dt)^3 Q}{2} \quad (5)$$

where

IP02 Attachment C

Q is the process (plant) noise variance. The ratio of the plant noise to the measurement noise determines the time constant of the Kalman filter. A recommended value for Q is $(1.61)^2 \frac{ft^2}{s^4}$ for steady state tracking and $(8.05)^2 \frac{ft^2}{s^4}$ during maneuvers (see maneuver detection below).

4.3 Residual Variance

The residual (or innovations) variance is calculated as explained by equation (6):

$$\mathbf{S}_v^2 = \mathbf{S}_{\hat{z}}^2 + \mathbf{S}_{z_m}^2 \quad (6)$$

where

$\mathbf{S}_{z_m}^2$ is the variance of the barometric altitude measurement. The recommended nominal value for this parameter for barometric altimeters is $36 ft^2$.

4.4 Maneuver Detection

The residual variance is used to detect maneuvers. The track residual (\mathbf{n}) consists of the difference between the new measurement and the measurement prediction (from equation 2):

$$\mathbf{n} = (z_m - \hat{z}) \quad (7)$$

A maneuver is detected when the residual is greater than a threshold based on the residual variance, i.e., if:

$$v^2 > k \mathbf{S}_v^2 \quad (8)$$

(where k is a unit-less constant -- an adaptation parameter with a recommended value of 9), then a maneuver is declared.

If a maneuver is detected the covariance matrix extrapolation is recalculated as per section 4.2 with the higher value of Q, or process noise, assumed. The higher value for Q results in a higher gain, and less measurement smoothing. This is appropriate during a maneuver. After recalculating the predicted covariance matrix, computation resumes as described in the steps below.

4.5 Filter Gain

The gain vector (\mathbf{w}) is then calculated according to equations (9) and (10):

$$\mathbf{w}_0 = \frac{\mathbf{S}_{\hat{z}}^2}{\mathbf{S}_v^2} \quad (9)$$

$$\mathbf{w}_1 = \frac{\mathbf{S}_{\hat{z}}^2}{\mathbf{S}_v^2} \quad (10)$$

4.6 State Estimate Smoothing (Update)

The update of the state estimate is performed according to equations (11) and (12):

$$\hat{\mathbf{z}} = \hat{\mathbf{z}} + w_0 (z_m - \hat{\mathbf{z}}) \quad (11)$$

$$\hat{\mathbf{z}} = \hat{\mathbf{z}} + w_1 (z_m - \hat{\mathbf{z}}) \quad (12)$$

where

z_m is the current position measurement.

4.7 Covariance Matrix Update

The update of the covariance matrix is then performed according to equations 13, 14, and 15:

$$\mathbf{S}_{\hat{\mathbf{z}}}^2 = (1 - w_0) \mathbf{S}_{\hat{\mathbf{z}}}^2 \quad (13)$$

$$\mathbf{S}_{\hat{\mathbf{z}}} = (1 - w_0) \mathbf{S}_{\hat{\mathbf{z}}} \quad (14)$$

$$\mathbf{S}_{\hat{\mathbf{z}}}^2 = \mathbf{S}_{\hat{\mathbf{z}}}^2 - w_1 \mathbf{S}_{\hat{\mathbf{z}}} \quad (15)$$

The update of the state and covariance completes the Kalman filter operations for the current measurement.

5.0 Conclusions

A formulation for a simple, two state, Kalman filter which may be practical for smoothing barometric altitude measurements has been presented. The filter accepts as input barometric altitude measurements.

Jonathan B. Hammer
Principal Engineer
MITRE Corporation
McLean, Virginia